IrrigRotation, a time continuous soil water balance model.

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Abstract: - The aim of this work was the development of the IrrigRotation software which is a soil water balance simulation model, based on the dual Kc methodology, that performs the soil water balance continuously in time using a daily time step. This continuous simulation allows to overcoming one of the greatest sources of uncertainty in the use of water balance models, which is the amount of available water in the soil profile at the beginning of the simulation. Thus, the initial error is diluted over the data time series, loosing is relevance. This model was built to be more flexible as possible, regarding the time series intervals, simulating time intervals from one day up to several years. The IrrigRotation can be applied either at a field level or at a regional level allowing the assessment of regional water irrigation requirements, trough its integration into the GIS software Geomedia 6.0. This model was implemented following an information system (IS) approach, and is composed by a graphic user interface, by several mathematical modules and a database. The methodology developed in this model, due to its continuous characteristic allows to consider the water needs of a sequence of crops and taking into account the water stored in the soil profile during the off-season time period, using a soil reservoir calculated according to the deepest root of the crop sequence/rotation. This way is possible to take into account the water requirements of a sequence of crops, including crop rotations, in opposition to traditional water balance models such as CROPWAT, ISAREG, PILOTE or more recently the SIMDualKc which typically perform the soil water balance only for the irrigation season and considering only one culture. The model was experimentally applied and tested for the Beja region, in Alentejo South of Portugal, providing irrigation requirements information based on the soil, crop, rotation scheme, climate and irrigation systems data. Weather data was obtained from a nearest meteorological station (Quinta da saúde - Beja).The first version of this system was successfully developed, allowing to compute the irrigation requirements of the sugar beet-maize-tomato-wheat crop rotation for the Beja region for the 2003-2007 period. Tests preformed evidence good model results.

Key-Words: - Irrigation, Crop rotations, Crop water requirements, Soil water balance, Water management, Simulation models, Information systems, GIS.

1 Introduction

Several studies indicate the need to improve irrigation management and practices, and the definition of water saving strategies to increase irrigation performances, including the reduction of the environmental impacts. In fact, the water management in irrigated agriculture is extremely difficult to perform by farmers and irrigation project managers, because requires the handling of many agronomic, environmental and economics variables.

Proper irrigation planning and water resources management require the availability of an accurate tool. Thus, it was created this Information System (IS) intended to aid the planning and the analysis of the farmer's irrigation practices, and to provide a tool to make easier the irrigation management of the crops. This IrrigRotation software allows to compute crop irrigation requirements and irrigation scheduling. This model performs a time continuous soil water balance, enabling to simulate the water requirements of one crop rotation, in opposition to traditional water balance models such as CROPWAT [16], ISAREG [17], PILOTE [13] or more recently the SIMDualKc [14] which typically perform the soil water balance only for the irrigation season and considering only one culture. This IrrigRotation model (Fig.1) computes crop evapotranspiration (ET_c) and perform soil water balance simulation based on the dual crop coefficient (Kcb + Ke) approach [1, 2, 4], which is especially suitable, for high frequency irrigations and for partial field cover crops, as well to consider the evaporation of soil layer during the off-season-period.

This IrrigRotation software was developed at farm-level using daily data, and is the core model of a more complex information system that is being developed to assess the impacts of the climate change on the irrigated agriculture and irrigation systems at a regional level.

This paper describes the IrrigRotation software, its algorithm and data structure, and its connection to the GIS, showing its application to the Beja region, South of Portugal adopting the sugar beet-maize-tomato-wheat crop rotation. Further improvements being performed to this IS concern the adoption of more geographic data to input the model, namely the use of spatial interpolated meteorological data and the consideration of the Digital Elevation Model (DEM), and the integration of more analysis models.

2 Water balance modeling

The time continuous soil water balance model developed in this work, is composed by 3 main components: the ETc calculation, the water balance itself and the generation of the crops sequence. In the following sections these components will be described in more detail.

Fig.1 presents the water balance algorithm. In this Figure 1 it can be see the interaction between the different program modules and the main input and output data required by the program.

The crops irrigation requirements are computed taking into account the water stored in the soil profile not only during the irrigation season but also during the off-season period, after crop harvesting, and adopting a soil reservoir calculated according to the deepest root of the crop rotation.

2.1 Crop Evapotranspiration

The methodology adopted to compute the soil water balance and ETc (Eq.1) follows the dual Kc approaches proposed by Allen *et al*. [1, 2, 4] which is defined by:

$$ET_c = (K_s K_{cb} + K_e) ET_o \qquad (1)$$

where: ETc is crop evapotranspiration [mm d-1], Kcb is the basal crop coefficient [], Ke is the soil evaporation coefficient [], Ks is the water stress coefficient [] and ETo is the reference crop evapotranspiration [mm d-1].

Reference crop evapotranspiration (ETo)

The reference evapotranspiration (ETo) is computed using the FAO Penman-Monteith (FAO-PM) method [1, 2], expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (2)$$

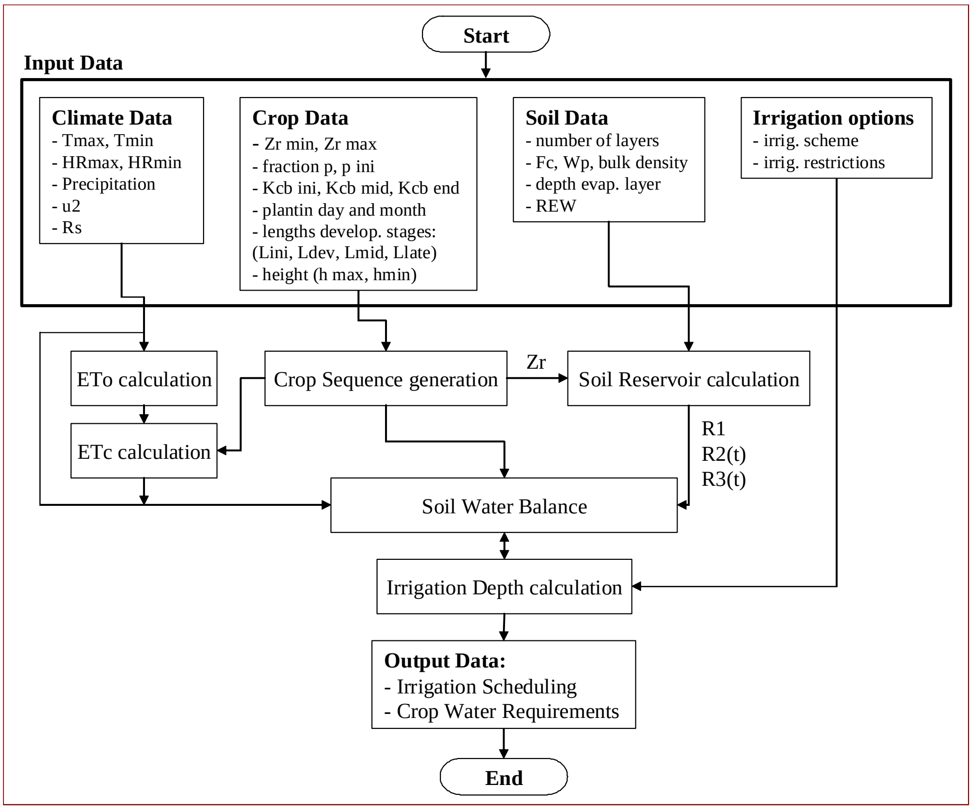

Fig.1 – Flowchart of the continuum water balance model.

Where:
ET_o – reference evapotranspiration [mm day^{-1}],
R_n – net radiation at crop surface [MJ m^{-2} day^{-1}],
G – soil heat flux density [MJ m^{-2} day^{-1}],
T – air temperature at 2 m height [ºC],
u_2 – wind speed at 2 m height [m s^{-1}],
e_s – saturation vapour pressure [kPa],
e_a – actual vapour pressure [kPa],
e_s-e_a – saturation vapour pressure deficit [kPa],
Δ – slope of vapour pressure curve [kPa ºC^{-1}],
γ – psychrometric constant [kPa ºC^{-1}],

When there is not available all the climate parameters necessary to use the FAO-PM method, the program allows calculate ETo using the Hargreaves method, using only temperature, which present results very close to the FAO-PM [21, 19].

Dual crop coefficient

The dual crop coefficient calculation is conducted on a daily basis and is recommended when improved estimates for ETc are needed, *e.g.* to schedule irrigations on a daily basis for individual fields [1].
The methodology adopted to compute ETc follows the dual Kc approach proposed by Allen *et al*. [1, 2] which is defined by:

$$K_c = K_{cb} + K_e \qquad (3)$$

or when the soil is under water deficit conditions

$$K_c = K_s K_{cb} + K_e \qquad (4)$$

The calculation procedure used to compute ETc is represented in Fig.2 and consists of:

1. The acquisition and gathering of the soil, climate, crop and irrigation system data. Climate data includes the estimation of ETo, and crop data includes the identification of the locally adjusted lengths of the four crop growth stages, and the selection of the corresponding tabled Kcb coefficients (e.g. the Kcb tabled by Allen *et al.* [1]);
2. Adjusting of the selected tabled Kcb to local climatic conditions and respective calculation for each day of the growing period according to the crop grow stage;
3. The calculation of daily Ke values, to estimate soil evaporation (E), uses the methodology updated by Allen *et al.* [2], including the estimation of soil cover (fc), soil wetted (fw), soil wetted and exposed fractions (few), and the determination of evaporation reduction coefficient (Kr) and water stress coefficient (Ks);
4. The calculation of the daily ETc (Eq.1) with the "actual" crop coefficient (Kc act) given by Eq.4, and daily soil water depletion.

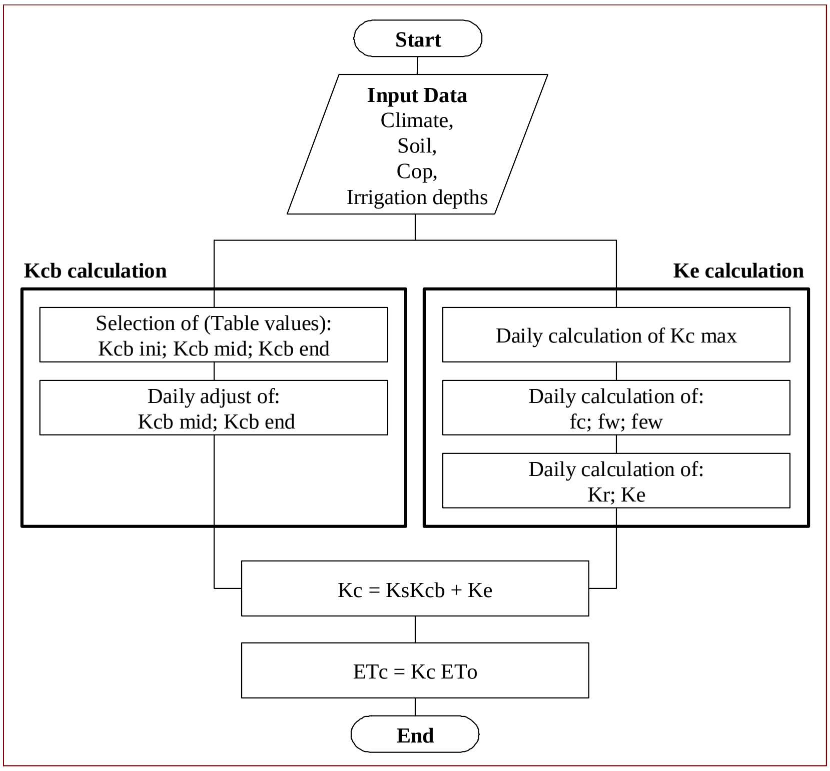

Fig.2 – Algorithm of the ETc calculation model.

2.2 Continuum water balance

The continuous simulation of the soil water balance allows to overcoming one of the greatest sources of uncertainty in the use of water balance models, which is the amount of available water in the soil profile at the beginning of the simulation. For instances, in the clay soils of Beja with Total Available Water (TAW) of about 250 mm/m [5], this uncertainty can present in a extreme case something like up to 40% of error, in the soil water balance, for each irrigation season. Thus, with this continuous water balance simulation the initial error is diluted over the data time series, loosing is relevance.

Should be noted that the magnitude of this error grows with the value of TAW, and thus the error reduction is more relevant the greater the value of TAW.

The soil water balance model developed in this work presents 3 different layers, as represented in Fig.3. The upper layer R1, corresponds to the soil layer where occurs soil evaporation together with plants transpiration, the second layer R2(t) corresponds to the portion of soil occupied by the roots where the water is withdrawal only by root extraction (transpiration) and is thickness increases during the culture growing cycle, the bottom layer R3(t) is the soil region that lies between the actual crop root depth Zr(t) and the maximum root depth achieved in the rotation (Zr Max_rot). This R3(t) layer, like the previous R2(t), presents a time variable thickness in function of the roots growing cycle along the crop rotation.

The irrigation decision is taken based on the values of the available soil water (ASW) of the R2 layer, and taking into account the following irrigation options:

- Do not irrigate;
- Optimum irrigation;
- Irrigate between two selected thresholds MAD1 and MAD2 (MAD – Management Allowed Depletion),
- Minimum interval of days,
- Constant interval of days;
- Restriction on the maximum volume of water,
- Constant irrigation depth,

The soil water balance equation adopted in this model is defined as (Teixeira *et al*. [18]):

$$\Delta R = \left(Pe + Vz + Ir + Gc - ETc - Dr\right)\Delta t \qquad (5)$$

Where:

ΔR – variation of the soil water reserve in the Δt time interval [mm],

Pe – effective precipitation [mm],

Vz – water stored in the deeper soil layer (R3(t) – Fig.3) [mm],

Ir – irrigation depth [mm],

Gc – ground water contribution [mm],

Dr – deep percolation losses [mm],

T – Time interval [days],

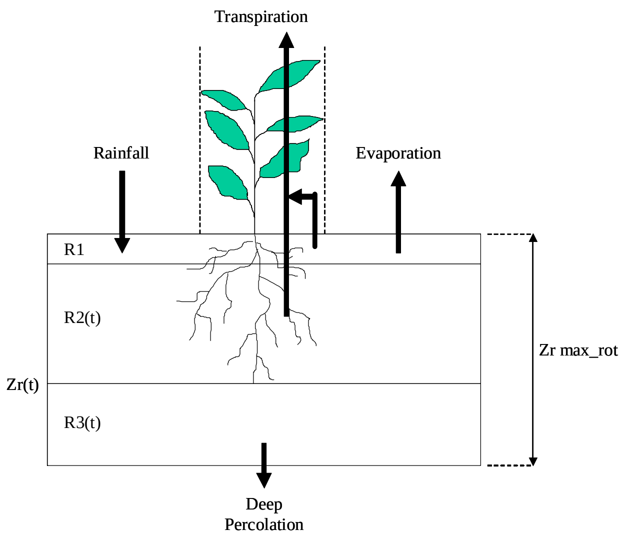

Fig.3 – Soil water balance of the root zone considering the deepest root of the rotation.

Obviously this equation was adapted to each one of the layers considered in the model, R1, R2(t) and R3(t), due to the different terms of the water balance considered in each one (Fig.3). Was chosen to carry out the simplification of Gc = 0 while it is not incorporated into this software a ground water contribution model, such as the methodology proposed by Liu *et al.* [12].

2.3 Crop sequences modelling

Since the simulation of irrigation continuously in time presents difficulties that the traditional soil water balance models can't solve there was the need to develop a module to generate the crop sequences including the off-season period. This module generates an array with a daily time step with the crop sequence as can be seen in Fig.4.

Additionally, this time continuous soil water balance allows to simulate the irrigation requirements of one crop rotation, which can be considered as one specific type of crops sequence.

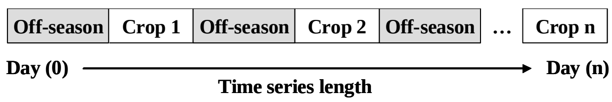

Fig.4 – Schematic representation of the crop sequence array with a daily time step.

3 IrrigRotation Information System

3.1 Program structure

The IrrigRotation software application (Fig.5) was developed in Visual Basic 2005 and includes a database in Access 2000. This software is compose by a computational module, a graphic user interface (GUI) and a database (Fig.5). The computational module was developed in modular manner allowing to be easily extended or integrated with other models.

In the development of the IrrigRotation information system (IS) was paid a particular attention to the data modeling, which was carried out using the entity-association model (E-A). The Database is one of the key elements of this IS, since its gather a great amount of field and weather data, and due to is integration function, since all models will be connect trough the Database. The Database stores information about the soil, crop, crop rotations, climate, irrigation systems and simulation data, which is a specific combination of the previous factors (Fig.5).

In fact, traditionally, in the models developed in the irrigation engineering the data have been treated as mere inputs and outputs, and most of the attention was given to algorithms design.

In this software, however, was adopted an information systems approach where data is so important as algorithms, since database will allow to perform data analysis through queries without needing to develop new software.

The model database is connected to a georeferenced database (GIS) as will be described in the next section of this paper, enabling the prediction of crop evapotranspiration at the irrigation project level as proposed by Allen *et al*. [3].

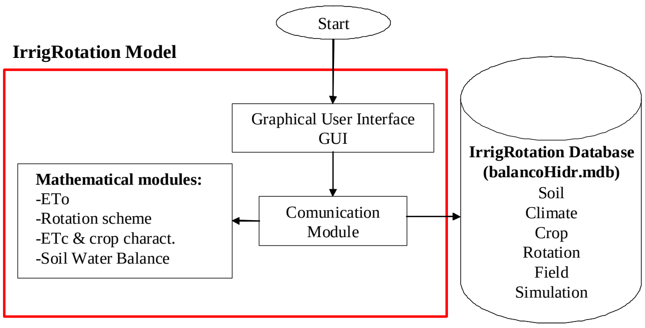

Fig.5 – Conceptual structure of IrrigRotation model.

3.2 Integration with GIS

Today is possible to assist to the development of many GIS tools in the agriculture domain for regional analysis [8], being this trend particularly significative in the management of water resources in agriculture [9, 20, 10, 11].

Hajare *et al*. [11] developed a GIS to evaluate the crop water requirements in any location trough the development of crop water requirements (CWR) isolines. The CWR computed by Hajare *et al*. [11] is based on a simple water balance consisting in the difference between effective rainfall and crop evapotranspiration.

The development of the IrrigRotation program is inserted in a broader goal of developing an information system, combining the IrrigRotation with GIS and other models, to support irrigation managers and decision-makers in their decisions relative to irrigation planning and management at a regional or irrigation project scale. In fact, coupling an irrigation model with the GIS technology expands its analysis scale to a regional level, enabling water resources planning and environmental studies [9, 20].

This system will be composed by several models integrated in a GIS environment, making use of the integrative capabilities of the GIS platform [15, 20]. The integration of this simulation model and is database in one major GIS structure as shown in Fig.6.

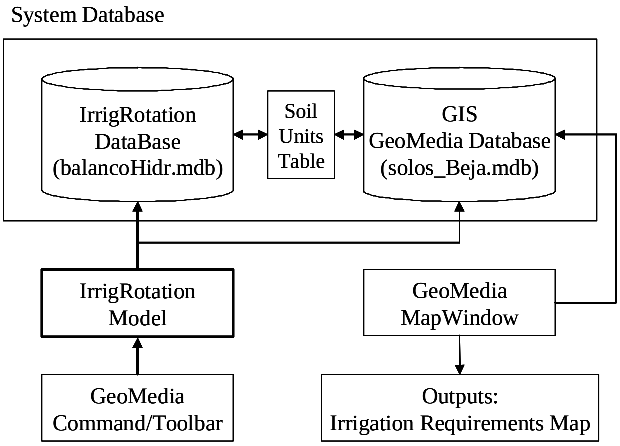

Fig.6 – GIS integration of the IrrigRotation model.

The IrrigRotation graphic user interface (GUI) is called from the GeoMedia map window by one toolbar which contains one command that makes the connection to this model, as can been seen in Fig.7. This command was developed in Visual Basic 6.0, using the GeoMedia command wizard (Fig.7).

This system database consists in the IrrigRotation database integration in one georreferenced database. This GIS database stores information about soils, contour levels, slopes and cartographic data. The development of the GIS database consisted in the combination of different vectorial thematic layers and of several alphanumeric data. The GIS database was developed in Access 2000, being the GIS database automatically generated by the GeoMedia 6.0, and afterwards edited and adapted to make the connection to the model data base.The IrrigRotation model reads data from this database and writes the simulation results in this GIS database allowing the generation of the irrigation requirement maps. Therefore, this GIS database enables the spatial analysis of the crop rotation water requirements.

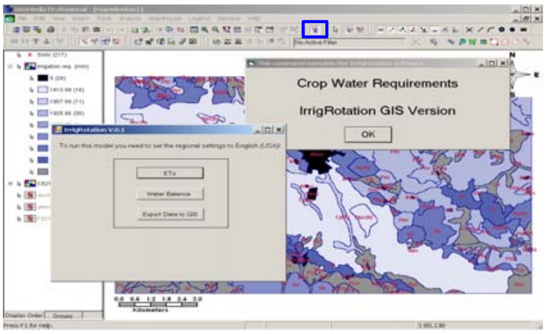

Fig.7 – IrrigRotation GUI and is connection to the GeoMedia software trough an toolbar (blue highlighted) which hold a command responsible of running the model.

3.3 Software operation
Input data is provided through the Access database and refers to: meteorological, crop, rotation, soil, field and irrigation options data. First, the user must enter into the database the data relative to the soil, crop and climatic data of the local region, with a daily time step, together with the description of the climatic station. When introducing or editing data the user can choose between importing ETo along with other climatic variables, or to compute ETo daily values using the IrrigRotation ETo calculation module. After, the user creates a simulation instance in the simulation table combining a field (soil and climate data series) with a crop rotation scheme and with the irrigation system and management options relative to each crop. Simulation results are stored in the results table. The results relative to the irrigation requirements can be either post-processed using the predefined queries in the database or be exported to a spreadsheet and analysed there. Relative to the GIS operation there is the need to edit and adapt the soil units table to fulfil the IrrigRotation data structure, being the simulation carried out trough the toolbar of the GeoMedia Map Window (Fig.6, 7).

4 IrrigRotation application
4.1 Application to the Beja region
The IrrigRotation IS was tested with data from Beja, Alentejo, South of Portugal, and it was considered a crop rotation representative of the region under analysis and the soil map number 521, with the goal to test this model and its capabilities. The Data used in this test was the following:

Greographical data: Geographical data imported to the GIS concerns several information of the Beja region corresponding to different vector layers, at the 1:25000 scale. These maps are a soils map (Fig.8), a digital elevation model or contour map, a slopes map and a cartographic map (IGeoE map number 521). Based on this data layers was produced the irrigation requirements thematic layer resulting from the simulation module calculations.

Soil Data: Soil data in this system is composed by georeferenced information relative to the spatial definition of the soil mapping units, which is provided by the IDRHa (Instituto de Desenvolvimento Rural e Hidráulica) soils map number 521 (Fig.8). The soils alphanumeric data was acquire from the Portuguese soils data collected by Cardoso [5].

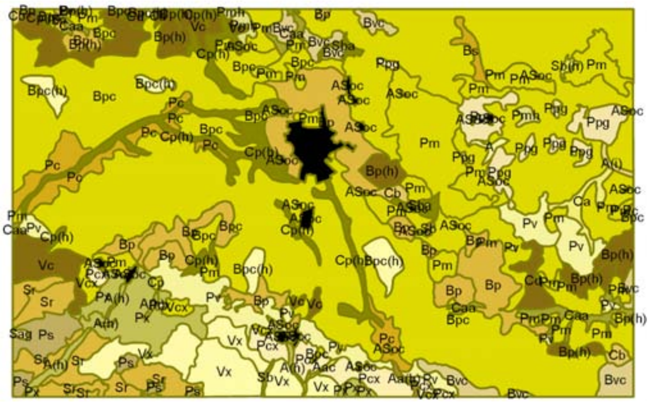
Fig.8 - Soils map number 521 refering to Beja soil mapping units (IDRHa).

In Table 1 is presented the soil properties of the BPc and Pv soils. The Bpc clay soil corresponds to the soil with the highest TAW value for this region, thus presenting the higher soil reservoir. The Pv Mediterranean soil, on the contrary, is the one presenting the lowest value of TAW. These two soils were used to perform a sensitivity analysis to the irrigation simulation, comparing the results achieved by the biggest soil reservoir with the smallest one.
It should be noted that was chosen, during the modeling process, to adopt the use of a custom evaporable soil layer depth, depending on the sensitivity of the user. In this study case was adopted a thickness of only 0.02 m (Table 1) instead of 0.10-0.15 cm recommended by Allen *et al*. [1, 2] since these values result in a very high number of irrigation events during the initial development stage, which is not realistic for the Portuguese conditions. In fact, in southern Portugal, with exception for emergence irrigations, is not normal to irrigate during the initial period of the crops.

Table 1 – Soil parameters of the BPc and Pv soils

Soil					
BPc	**Evaporable layer**	Layer depth = 0.02 m		REW = 1.6 mm	
	Layer	**Top depth (m)**	**Bottom depth (m)**	**θFC m3/m3**	**θWP m3/m3**
	Ap	0	0.3	0.431	0.200
	B	0.3	0.65	0.475	0.231
	Bcca	0.65	0.9	0.507	0.263
	CcaC	0.9	1.2	0.429	0.197
Pv	**Evaporable layer**	Layer depth = 0.02 m		REW = 1.6 mm	
	Layer	**Top depth (m)**	**Bottom depth (m)**	**θFC m3/m3**	**θWP m3/m3**
	Ap	0	0.2	0.298	0.174
	B	0.2	0.4	0.356	0.207

This 0.02m value was obtained through an iterative process where were simulated different thickness values for the evaporable layer, until was reached an agreement between the simulation results and the field reality.

Crop and rotation data: the crop rotation adopted to test this system was the sugar beet-maize-tomato-wheat crop rotation, recommended by Coelho [6]. The data inserted in the database relative to the crops was obtained from the FAO paper n.56 crop tables [1, 4] and is presented in Table 2.

Table 2 – Crops parameters of the sugar beet, maize, tomato and wheat crops

	Crop			
	Sugar beet	**Maize**	**Tomato**	**Wheat**
Plant day	15	10	2	1
Plant month	11	4	5	11
L ini	45	30	30	30
L dev	75	40	40	140
L mid	80	50	45	40
L late	30	30	30	30
kcb ini	0.15	0.15	0.15	0.15
kcb mid	1.15	1.15	1.1	1.1
kcb end	0.5	0.15	0.8	0.15
root min (m)	0.15	0.15	0.15	0.15
root Max (m)	0.7	1	0.7	1.8
p ini	0.6	0.6	0.5	0.6
p	0.55	0.55	0.4	0.55
Height Max (m)	0.5	2	0.6	1
Height min (m)	0	0	0.07	0

Meteorological data: weather data, to peform the soil water balance was obtained from a nearest meteorological station located in Quinta da Saúde, Beja. In Table 3 are listed the characteristics of the Beja automatic weather sation. Belongs to the SAGRA (Sistema Agrometeorológico para a Gestão da Rega no Alentejo) meteorological network, and can be accessed trough the COTR (Centro Operativo de Tecnologia do Reagadio) WEB site [7]. The time series have a daily time step and was considered the 2003 to 2007 period. Table 4 presents the month averages of the climate parameters considered in this work.

Table 3 – Characteristics of the Beja weather station (COTR [7])

Longitude*	07º 53' 06" W
Latitude*	38º 02' 15" N
Altit. (m)	206
Alt. anem. (m)	2
Series Beginning	1/1/2003
Series end	23/07/2007

* Datum 73

4.2 Results

The results presented in this section are the irrigation requirements map produced by the GIS (Fig.9) and the results obtained by the two soil units, the Bpc - clay soil and the Pv - mediterranean soil that illustrate the model performance. This Bpc soil results were chosen since is the more representative soil mapping unit in the soils map number 521 (Fig.9) and because is the soil with the highest soil reservoir value. On the other hand the Pv soil was selected due to its reduced value of the soil reservoir. This way is possible to compare the simulation results obtained by both of them in order to assess the impact of the soil TAW in the simulation results.

Fig.9 shows that the irrigation requirements of the rotation considered present a significant spatial variation, between the soils considered.

Table 4 – Month averages of the climate parameters: temperature (Tmax, Tmin), relative humidity (HRmax, HRmin), wind speed (u2), solar radiataion (Rs), precipitation (P) and reference evapotranspiration (ETo), relative to the 2003-2007 period of the Beja weather station.

	Month averages							
Month	**Tmax**	**Tmin**	**RH max**	**RH min**	**u2**	**Rs**	**P**	**ETo**
	ºC	**ºC**	**%**	**%**	**m/s**	**MJ/m2/day**	**mm**	**mm (day)**
Jan	15.28	4.32	94.23	56.84	1.82	9.68	33.33	1.27
Feb	16.30	5.08	94.90	54.54	2.00	12.19	49.11	1.76
Mar	19.41	6.85	94.25	47.79	2.11	17.12	38.74	2.82
Apr	22.31	8.34	93.95	43.10	2.02	21.90	39.58	3.88
May	26.64	10.81	90.83	34.62	2.01	25.90	25.42	5.23
Jun	31.80	14.54	88.41	30.20	2.18	28.81	13.50	6.61
Jul	33.95	15.29	84.78	25.19	2.43	29.75	1.45	7.31
Aug	35.01	16.73	82.41	24.36	2.25	26.07	5.60	6.76
Sep	31.31	14.83	83.88	28.18	2.08	21.21	22.05	5.04
Oct	24.50	12.94	92.07	46.00	2.27	13.67	131.42	2.88
Nov	19.06	8.71	93.97	55.20	1.98	9.94	95.67	1.60
Dec	15.53	5.19	93.89	57.11	2.05	9.08	46.91	1.22

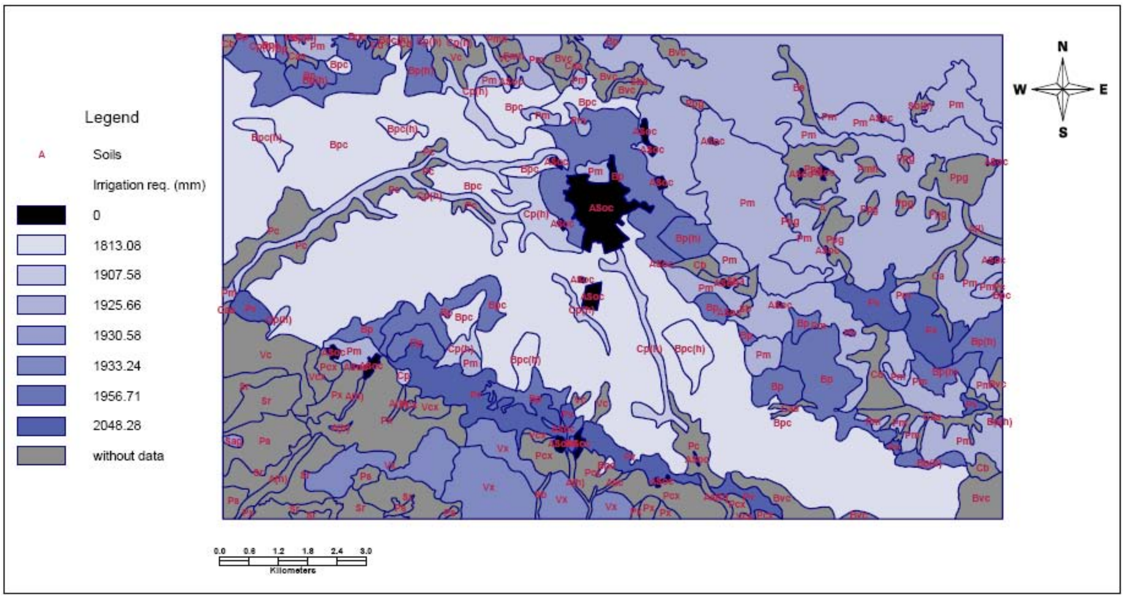

Fig.9 – Crop irrigation requirements maps (mm) for the sugar beet-maize-tomato-wheat crop rotation in the Beja region for the 2003 to 2007 period.

From Fig.10 is possible to see the variation of the soil water content not only during the irrigation season, but also along the off-season period what makes possible to transfer the remain water in the soil at the end of one crop to the next one. Table 5 presents the irrigation requirements, the number of irrigation events and the average irrigation depth obtained for each crop, for the BPc and Pv soil, with the IrrigRotation Model. Table 5 also shows the total deep percolation that occurs through the entire data series considered, with a value of 616 mm to the Bpc and 1027 mm to the Pv soil. This difference is due to the amount of water stored in the soil profile due to the higher TAW value of the BPc. In the case of soils with an high soil reservoir and profile depth the water is stored in the deeper soil layers during the off-season period and in the course of crops with shallow roots (Fig.10a). This water is used later by the other cops of the rotation, allowing to reduce the irrigation requirements of the entire data series from 2021 mm (Pv) to 1811 mm (BPc) as shown in Table 5.

The good results obtained with the tests performed during this trial provide a high level of confidence to the results expected for the field application of this model.

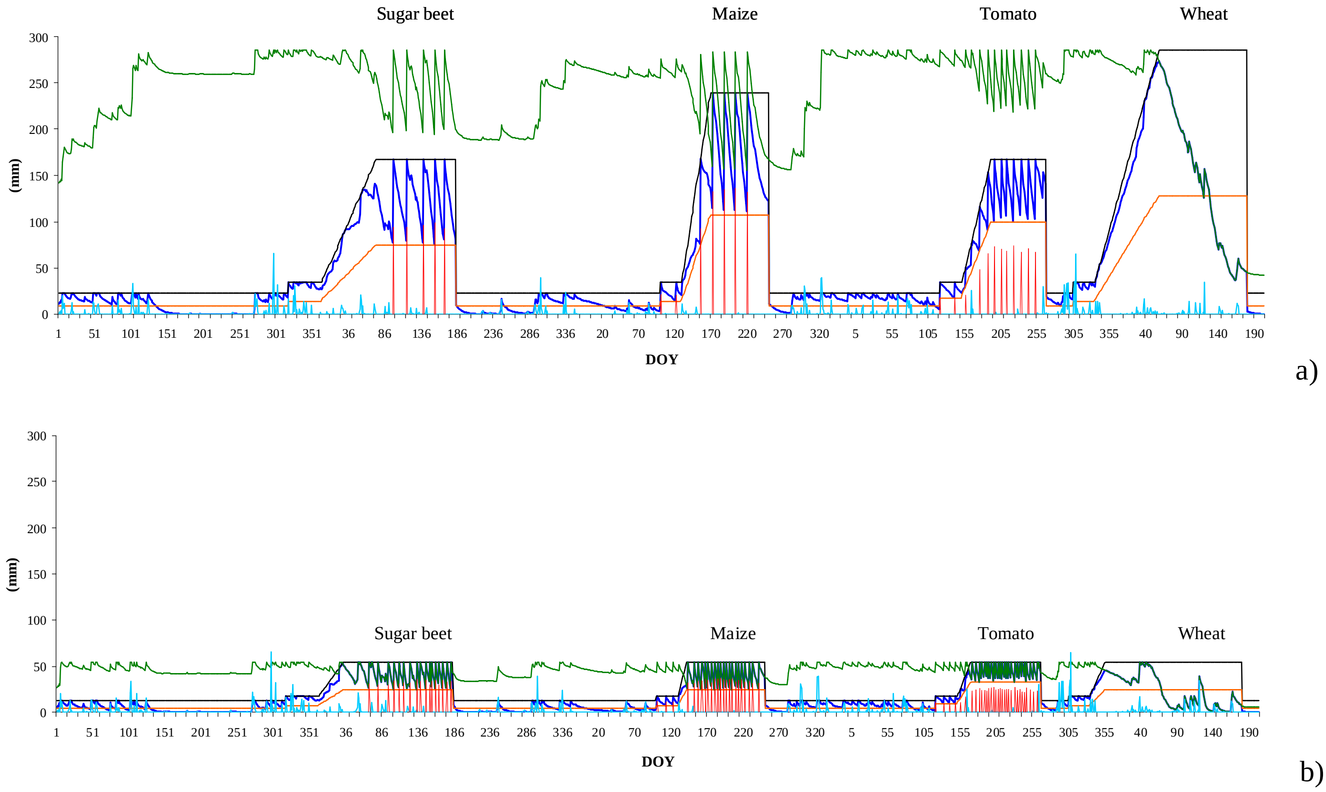

Fig.10 – Simulated soil water content curves where (——) is the available soil water in the root zone, (——) is the available soil water for the deepest root of the rotation (Zr max_rot). Lines represent (——) TAW and the (——) threshold for no stress. Spikes correspond to (——) rainfall and to (——) irrigation events, **a)** for the BPc clay soil and **b)** for the Pv mediterranean soil.

Table 5 – Crops irrigation requirements, number of irrigation events, average irrigation depth and deep percolation obtained with the IrrigRotaion model for the BPc and Pv soils

Crop	order number	Irrigation Requirements (mm)		Number of Irrigation Events		Average Irrigation Depth (mm)	
		BPc	Pv	BPc	Pv	BPc	Pv
Sugar beet	1	476	556	5	17	95	33
Maize	2	671	756	7	24	96	31
Tomato	3	664	710	12	32	55	22
Wheat*	4	0	0	0	0	0	0

Total data series	BPc		Pv	
	Deep Percolation (mm)	Irrigation Req. (mm)	Deep Percolation (mm)	Irrigation Req. (mm)
	616	1811	1027	2021

*rainfed

5 Conclusion

This software application for irrigation analysis was developed and experimentally applied to the Beja region showing to be able to compute crop sequence/rotation irrigation requirements at field or regional level, aiming to improve crop yield and water productivity.

Through the development of a time continuous soil water balance model, and its implementation in the IrrigRotation software, was possible to reduce the uncertainty level involved in the calculation of the soil water balance. The amount of water stored in the soil profile at the beginning of each crop is calculated by the model rather than arbitrary assigned as happens with most of the existent soil water balance

models. Additionally, this IrrigRotation IS enables to assess the traditional practice of crop rotations from a water resources management point of view.
Further developments comprise improvements in the GIS integration; the implementation of this system to one or more irrigation projects to test the systems true capacities to support the improvement of irrigation techniques; the improvement of the IrrigRotation IS with the integration of other models, such as economic, water productivity and environmental models; and the integration of more geographic information such as the terrain slope derived from the digital terrain model, several techniques of spatio-temporal interpolation of the meteorological data, and including the use of remote sensing data.

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